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TRAJECTORY APPROACHES FOR LAUNCHING HYPERSONIC FLIGHT TESTS (PREPRINT)

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High Speed Systems Division

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14. ABSTRACT
This paper presents some approaches toward designing trajectories for hypersonic testing at up to Mach 10 speed using a reusable rocket-powered first stage. The motivation behind the paper is the Defense Advanced Research Project Agency (DARPA) eXperimental Spaceplane-1 (XS-1) program that is focused on low cost responsive access to space of which the first stage can also be used for hypersonic testing. Trajectories were analyzed using NASA's Program to Optimize Simulated Trajectories (POST) code to look at different ways of flying to Mach 10 with a reusable first stage rocket. These trajectories are good starting points for how to setup a trajectory simulation to meet hypersonic testing needs.

15. SUBJECT TERMS
responsive and reusable rocket plane, trajectory analysis, return to launch site trajectory, hypersonics

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Trajectory Approaches for Launching Hypersonic Flight Tests

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This paper presents some approaches towards designing trajectories for hypersonic testing at up to Mach 10 speed using a reusable rocket powered first stage. The motivation behind the paper is the DARPA XS-1 program that is focused on low cost responsive access to space of which the first stage can also be used for hypersonic testing. Trajectories were analyzed using NASA's POST code to look at different ways of flying to Mach 10 with a reusable first stage rocket. These trajectories are good starting points for how to setup a trajectory simulation to meet hypersonic testing needs.

Nomenclature

AFRL	=	Air Force Research Laboratory	nmi	=	nautical miles
BTU	=	British Thermal Units	POST	=	Program to Optimize Simulated Trajectories
DARPA	=	Defense Advanced Research Project Agency	PR	=	Puerto Rico
deg	=	degrees	psf	=	pounds per square foot
DPG	=	Dugway Proving Grounds	"q" or "Q"	=	Dynamic Pressure
FAST	=	Future responsive Access to Space Technologies	RBS	=	Reusable Booster System
ft	=	feet	SBIR	=	Small Business Innovative Research
g's	=	acceleration normalized by Earth's gravity	sec	=	seconds
kft	=	thousands of feet	VTHL	=	Vertical Takeoff Horizontal Landing
KSC	=	Kennedy Space Center	WSMR	=	White Sands Missile Range
lbs	=	pounds	XS-1	=	eXperimental Spaceplane 1

I. Introduction

THE U.S. Air Force over the past ten years has been investing in design studies and technologies to develop a partially reusable launch system to increase responsiveness and reduce costs for space access. These efforts began with the Operationally Responsive Space Analysis of Alternatives[1,2]. The main focus of the Air Force efforts evolved into developing a vertical takeoff horizontal landing (VTHL) Reusable Booster System (RBS). An RBS consists of a reusable first stage with an expendable upper stage (shown in Figure 1). The Space and Missile Center started an effort to lead to a flight demonstration that was called Affordable REusable Spacelift[3]. After that effort ended, the Air Force Research Laboratory (AFRL) had a program called Future Responsive Access to Space Technologies (FAST) that focused on developing efficient structures, ground operability, and adaptive guidance & control[4]. The FAST program was followed by a flight demonstrator program called RBS Pathfinder, which was to demonstrate the rocketback return to base flight maneuver[5]. The reader is encouraged to review the references cited in this paper to understand the motivation behind some of the decisions made for these efforts. Although a 2012 report by the National Research Council on RBS showed support for the RBS Pathfinder program, these technology efforts were stopped due to budget priorities and reduced customer support for the efforts[6]. A graphical summary of the technologies that were being developed under these efforts is shown in Figure 2.

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The Defense Advanced Research Project Agency (DARPA) has recently started a program called eXperimental Spaceplane-1 (XS-1) that is leveraging this technology investment[7]. XS-1 will focus on developing a high responsive launch system with a reusable first stage to drastically cut the costs of launching 3,000 – 5,000 lbs into orbit.

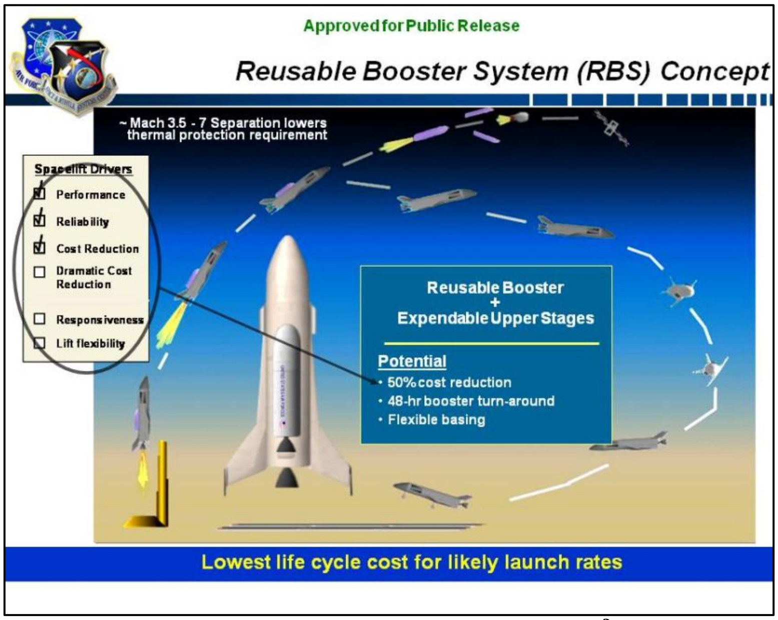

Figure 1. Overall Idea of the RBS Concept[3].

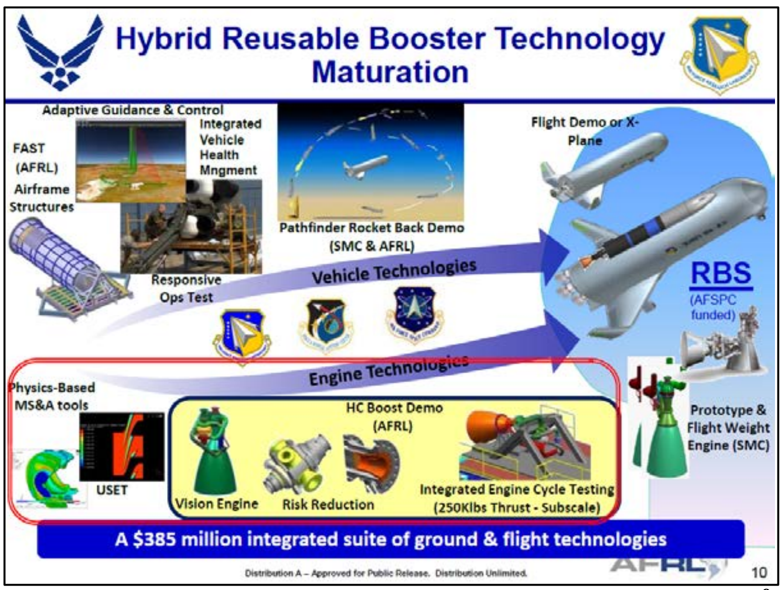

Figure 2. Graphical Summary of RBS Technologies Invested in by AFRL[8].

During the RBS activities, AFRL has also been investing in hypersonic technologies for a variety of uses including long range strike and penetrating Intelligence, Surveillance, Reconnaissance (ISR). As part of these efforts is to conduct flight experiments of specific technologies and flow phenomenon. Since hypersonic flight conditions can be very difficult and expensive to test on the ground, it is sometimes a better value to pursue a flight test effort.

Most of these hypersonic flight test efforts have been done under the HIFiRE program[9,10,11]. The HIFiRE program consisted of using existing solid rocket motor stacks to boost payloads up to hypersonic flight conditions. While this approach has proven to be successful, there are complications that arise integrating with the payload that increases cost and schedule. Many of these complications arise with having to get into the necessary flight conditions.

A recent Small Business Innovation Research (SBIR) topic titled "Launch Vehicle Systems Intended to Execute Suppressed Trajectories for Hypersonic Testing" was put out to attempt to improve upon the testing approaches in HIFiRE[12]. An additional way envisioned to approach hypersonic flight testing is to utilize a reusable rocket vehicle similar to what would be use for access to space. Part of the XS-1 program is to demonstrate a flight to at least Mach 10 (there are no specific parameters such as dynamic pressure or heat rate currently tied to this program objective). The main motivation behind this program objective is have a testbed platform to test technologies for hypersonic vehicle development. As a test bed, the technologies could be captive carried on the vehicle or be dropped off. Figure 3 presents some of the potential testing options envisioned that the XS-1 program could enable.

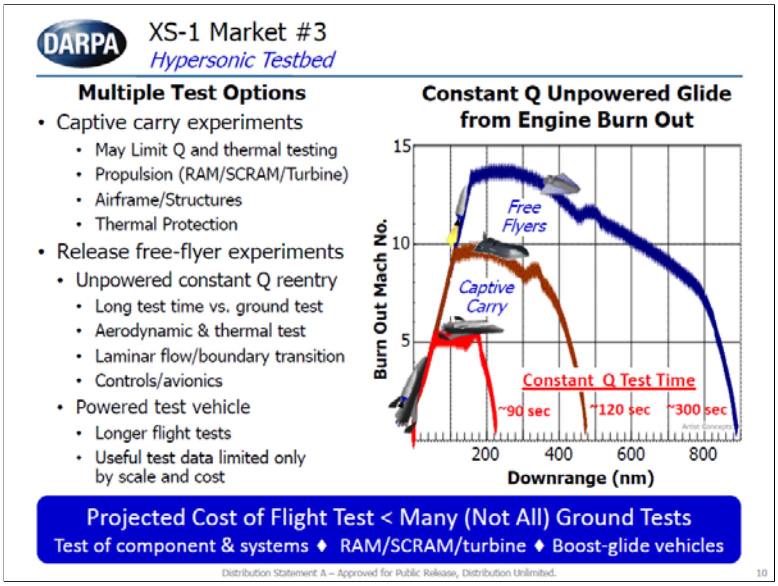

Figure 3. Chart from XS-1 Proposer's Day Showing Envisioned Use for Hypersonic Testing.

This paper will present some example approaches to flying hypersonic trajectories using a reusable rocket vehicle that is derived from AFRL's RBS efforts. There are many different options to how a trajectory could be designed to meet test requirements while taking into account range and overflight constraints. This author of this paper doesn't endorse any particular approach but intended to present industry and participants in the program some ideas of how to approach the Mach 10 and hypersonic testbed objectives of the XS-1 program.

II. Flight Conditions for Hypersonic Testing

As part of the above mentioned SBIR topic, hypersonic test windows were defined[13]. These windows focused on parameters that can be translated into an altitude and velocity. The four windows defined are propulsion/controls, boundary layer, aeroheating, and rocketback. The rocketback window is based on the work[14] done during the RBS Pathfinder program at AFRL. The other windows are mostly based on boost-glide type vehicles and hypersonic airbreathing vehicles technology needs. The trajectories presented in this paper will be plotted against these test windows. The parameters defining these windows are shown in Figure 4. The windows plotted as altitude vs. Mach number is in Figure 5.

For the XS-1 program, the Mach 10 test objective was set at that speed since it addresses many of the hypersonic aerodynamic flow physics for a reusable orbital space plane. Figure 6 illustrates this idea.

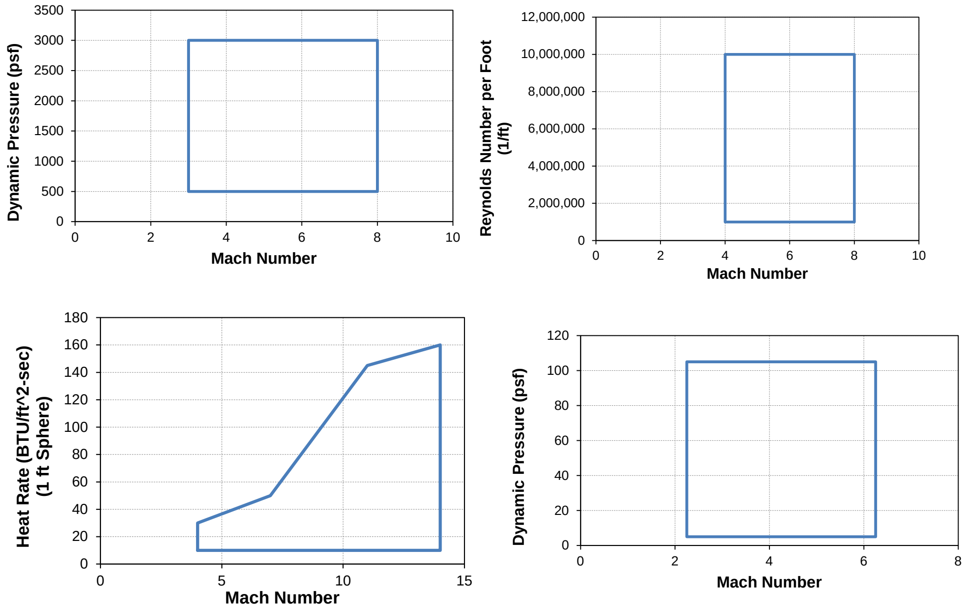

Figure 4. Plots Showing the Parameters that Defined the Hypersonic Test Windows.
Propulsion and Controls: Upper Left Boundary Layer: Upper Right,
Aeroheating: Lower Left Rocketback: Lower Right

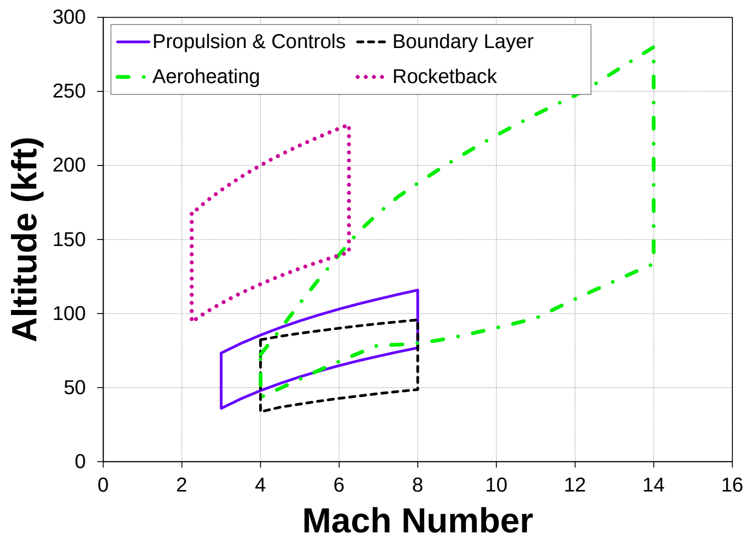

Figure 5. Hypersonic Test Windows Presented as Altitude vs. Mach Number from Reference 13.

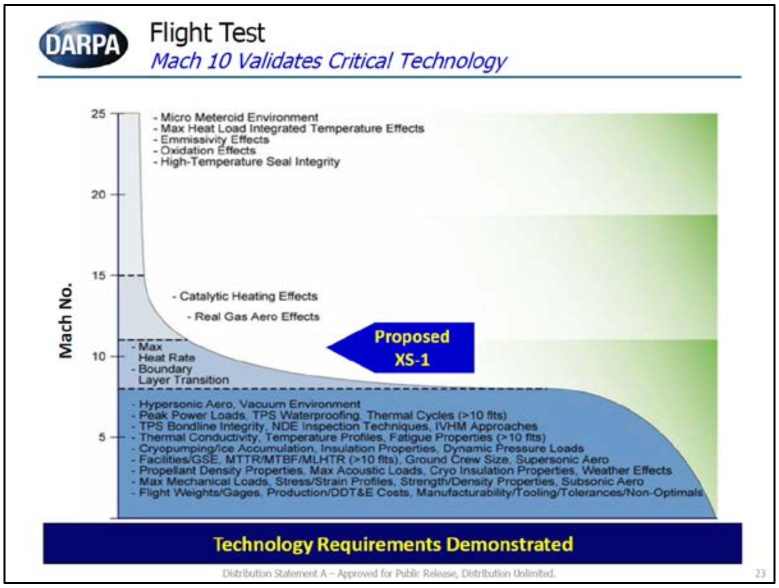

Figure 6. Chart from XS-1 Program Industry Day Illustrating the Hypersonic Flow Physics Addressed as a Function of Mach Number.

III. Vehicle Assumptions

The vehicle design used to generate the trajectories in this paper is a derivative the final vehicle design of AFRL's previous Future responsive Access to Space Technologies (FAST) program[15]. As part of the ground experiments for that effort, a reference flight system was designed up front and then modified at the end of the program using the lessons learned.

This vehicle design was sized based on 4 SpaceX Merlin engines[16] an capable of putting a 5,000 payload into orbit. For the work in this paper, the concept was scaled down to only having 2 Merlin engines. The outer mold line is shown in Figure 7. The vehicle's trimmed lift to drag aerodynamics is shown in Figure 8. The vehicle's weights and wing loading are listed in Table I.

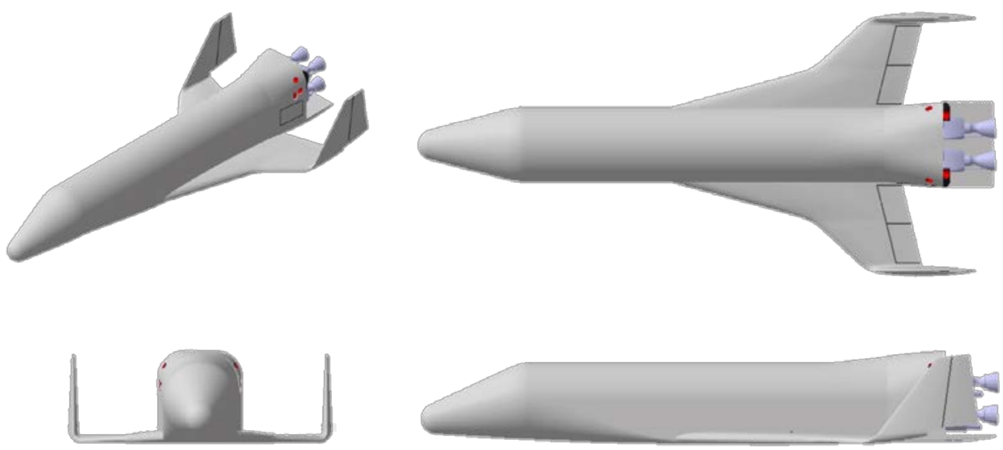

Figure 7. Outer Mold Line of the Vehicle Used for the Trajectories in this Paper.

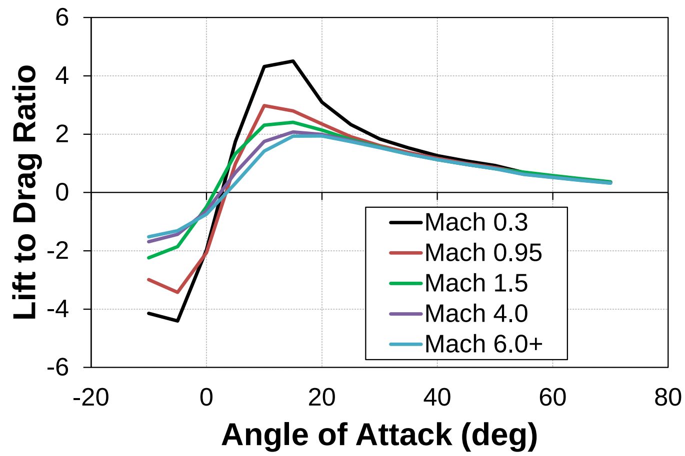

Figure 8. Trimmed Aerodynamic Properties Assumed for the Trajectories in this Paper.

Table I. Vehicle Sizing Specs for the Trajectories Presented in this Paper.

Gross Weight (lbm)	182,000
Propellant Weight (lbm)	145,600
Empty Weight (lbm)	36,400
Propellant Mass Fraction	0.80
Empty Vehicle Wing Loading (psf)	50.7

IV. Hypersonic Trajectories

As mentioned above, this paper presents examples of designing trajectories for hypersonic testing using a reusable first stage. While each of the approaches shown below have differences in the way the trajectory simulation is modeled an optimized, there are some commonalities between them. The trajectories in this paper are examples of how to fly to meet the Mach 10 program objective for the XS-1 program. There are many other ways to approach this trajectory problem. Specific needs for testing hypersonic technologies will drive the parameters to set the trajectory design.

All trajectory modeling was done in NASA's Program to Optimize Simulated Trajectories 2 (POST2)[17]. Each simulation starts with the rocket launching vertically for 3 seconds. After 3 seconds, the simulation then optimizes the pitch angle (inertial pitch angles, see POST's documentation for this definition). The pitch angles are still optimized even when the vehicle runs out of propellant and stops thrusting. When the vehicle starts to re-enter from sub-orbital flight and the dynamic pressure builds up to 30psf, the angle of attack of the vehicle is fixed at 40º. When the speed then reaches Mach 4, the angle of attack is set to 10º which is near the maximum lift to drag ratio for speeds below Mach 4 (as shown in Figure 8). As the vehicle glides from these conditions, the bank angle is adjusted by the optimizer to reach the landing location. To account for headwinds and energy management manuevers, the simulation ended at 50kft above the runway.

There are some additional ways to control the trajectory that are not considered in this paper. An example is to throttle the main engines. This can help extend test time and can help to suppress the trajectory (i.e. fly at lower flight path angles). Additionally, in-flight engine restart could be used to re-boost the vehicle. Additionally, during the ascent portion of the flight, vehicle roll and sideslip could be used to reach certain flight conditions (the trajectories in this paper only used pitch control during ascent). Furthermore, this effort did not look at releasing any free-flyer payloads. Finally, the use of any speed brake or other drag increase devices, which could help tailor trajectories were, not used.

The following sections present different approaches towards optimizing hypersonic testing trajectories. In each example, all trajectories reach Mach 10 at least once.

A. Initial Trajectories

Looking at Mach 10 trajectories with a reusable rocket vehicle started off with finding a locations from where to launch from and land at. Although there are other options, two options were looked at. The longer of the two options is launching from a launch pad near NASA's Kennedy Space Center (KSC) in Florida and landing at the Roosevelt Roads airport in Puerto Rico (PR). The other option looked at is to fly from the southern part of White Sands Missile Range (WSMR) and land at the Dugway Proving Grounds (DPG) in Utah.

The optimization of these trajectories used the above mentioned trajectory simulation for ascent and gliding. The optimization function was to minimize the normal loading on the vehicle throughout the entire flight. The constraints were to reach Mach 10 at least once during the flight and to only fly between -20º and 30º angle of attack during ascent.

Figure 9 through Figure 15 compares the flight conditions achieved during these trajectories. The heat rate of these trajectories is compared to a the re-entry from the STS-1 Space Shuttle flight data[18]. It can clearly be seen that longer flight of KSC to PR requires the vehicle to fly higher. The KSC to PR flight also flies faster than Mach 10 and reaches a heating rate comparable to the Space Shuttle re-entry. Both trajectories experience similar maximum dynamic pressures and both go through peaks during ascent and descent. However, the KSC to PR trajectory experiences a dynamic pressure peak during re-entry faster than the WSMR to DPG trajectory, Mach ~9 compared to Mach ~3.5. Due to the long distance, the KSC to PR trajectory used 30º angle of attack during re-entry.

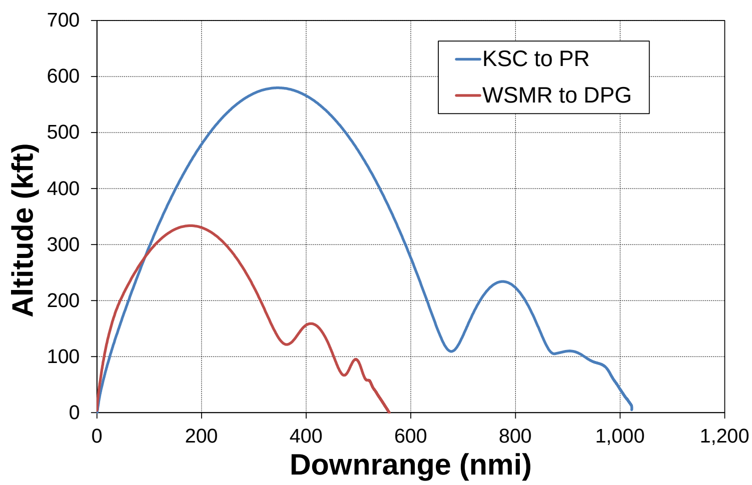

Figure 9. Altitude vs. Downrange for Initial Trajectories Looking at Possible Launch and Landing Locations.

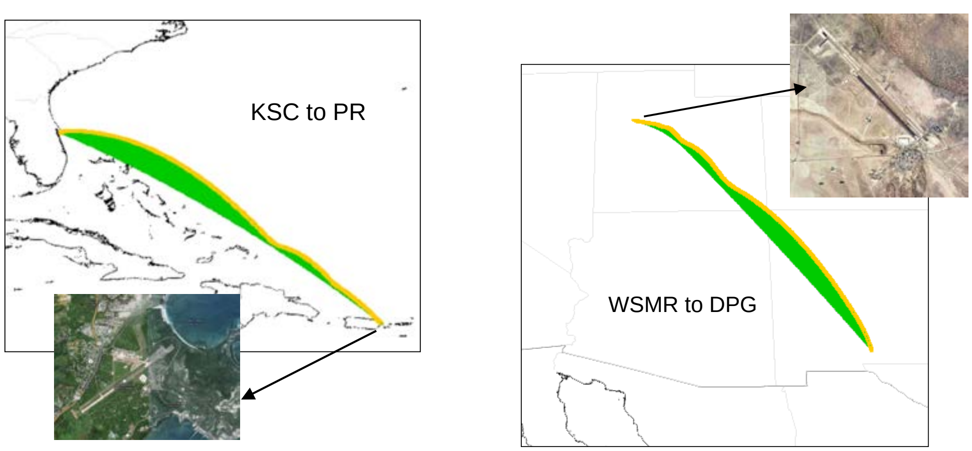

Figure 10. Map Overlays of Initial Trajectories.

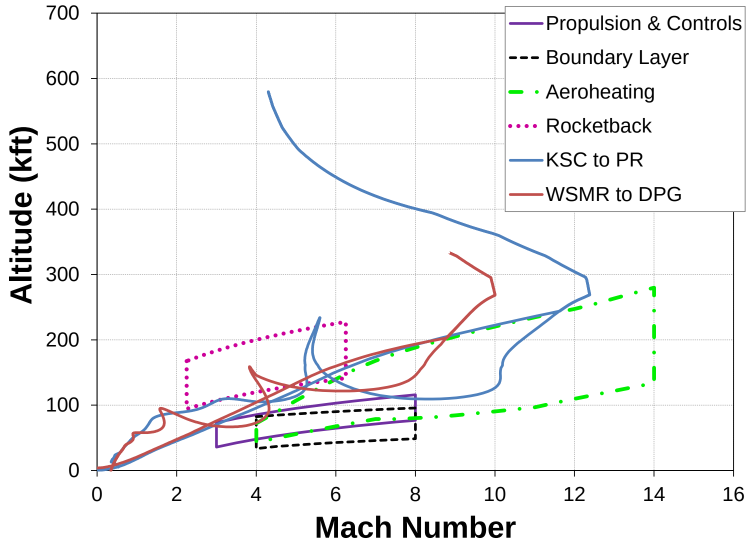

Figure 11. Initial Trajectories Plotted as Altitude vs. Mach Number and Compared Against the Hypersonic Flight Test Windows.

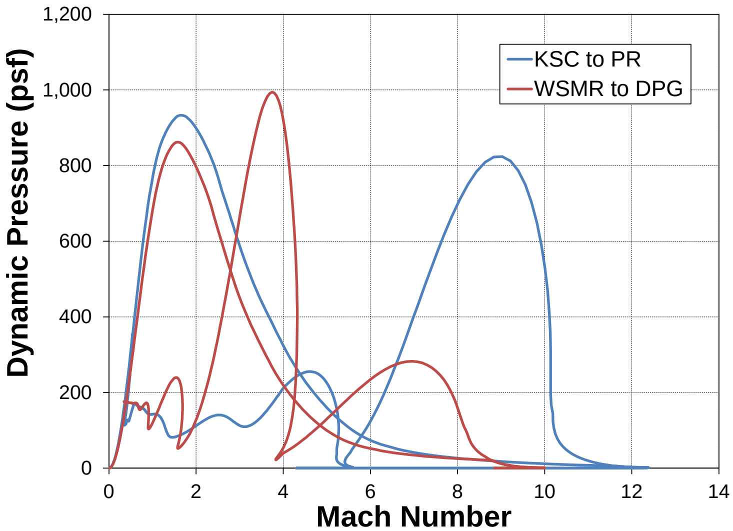

Figure 12. Initial Trajectories Plotted as Dynamic Pressure vs. Mach Number.

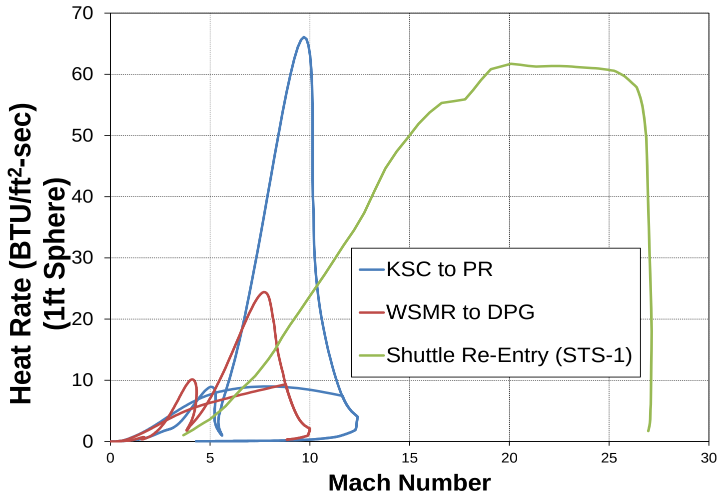

Figure 13. Initial Trajectories Plotted as Heat Rate vs. Mach Number.

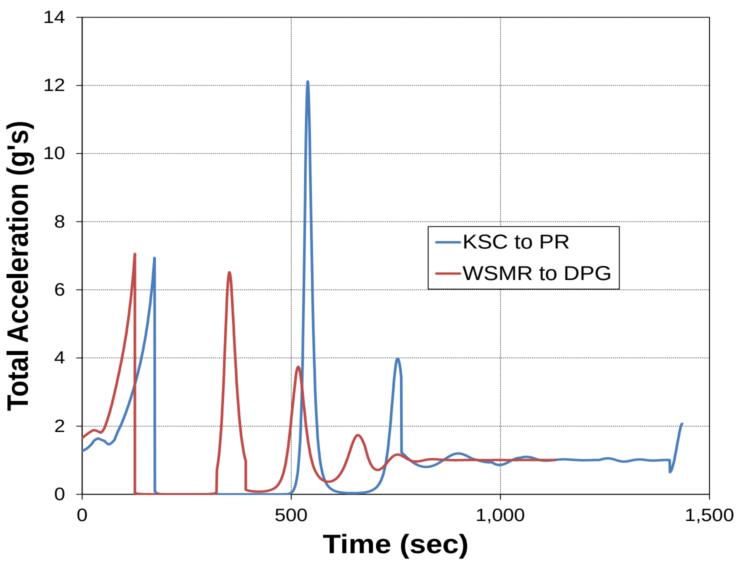

Figure 14. Initial Trajectories Showing Total Acceleration vs. Time of Flight.

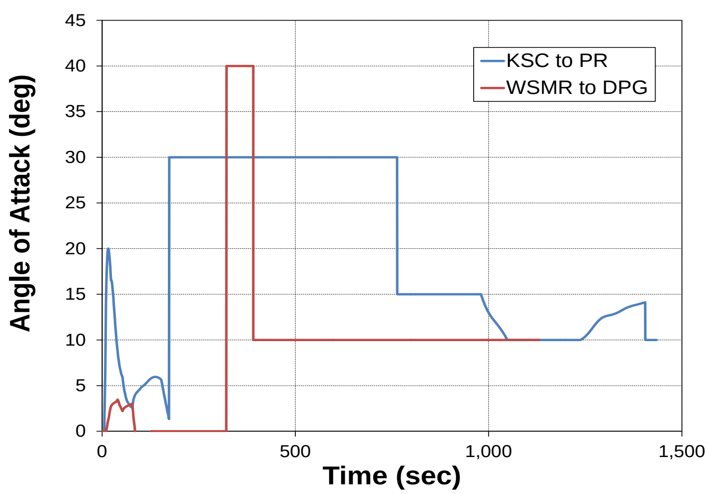

Figure 15. Initial Trajectories Showing Angle of Attack vs. Time of Flight.

B. Constrain Minimum Dynamic Pressure

After looking at two potential range options for the Mach 10 trajectory, alternatives to those trajectory approaches were performed to see how a trajectory could be tailored to meet potential test objectives. The WSMR to DPG trajectory was used for all of the following trajectories as it was the easiest to meet range requirements due to its shorter distance.

The optimization for the trajectories in this section added in a constraint to meet a certain minimum dynamic pressure during the flight (500psf, 1000psf, 1500psf, and 2000psf). The optimization function and other constraints are the same as the previous section. Reasons for setting dynamic pressure include test hypersonic propulsion components, testing the robustness of structure, and stressing a autonomous control system.

Figure 16 through Figure 21 present these trajectories. An observations from the results is that as the dynamic pressure constraint is increased in value, the trajectory as seen in Figure 16 becomes more overall mores suppressed flying at lower altitudes (which is necessary to increase the free stream density to help achieve the higher dynamic pressure). Another interest result is that the when the minimum dynamic pressure was set to 500psf, the trajectory optimized with a higher dynamic pressure of about 750psf. Furthermore, the Mach number at which the higher dynamic pressure occurred below Mach 2 which is no longer hypersonic. The dynamic pressure peaked during ascent (looking carefully at Figure 16 shows an early dip to get to the higher dynamic pressure). All trajectories did again go through an increase in dynamic pressure during descent at a speed slower than Mach 4. Although the trajectories did go through peak dynamic pressures at hypersonic speeds, they did achieve higher heating rates at Mach 10 and up.

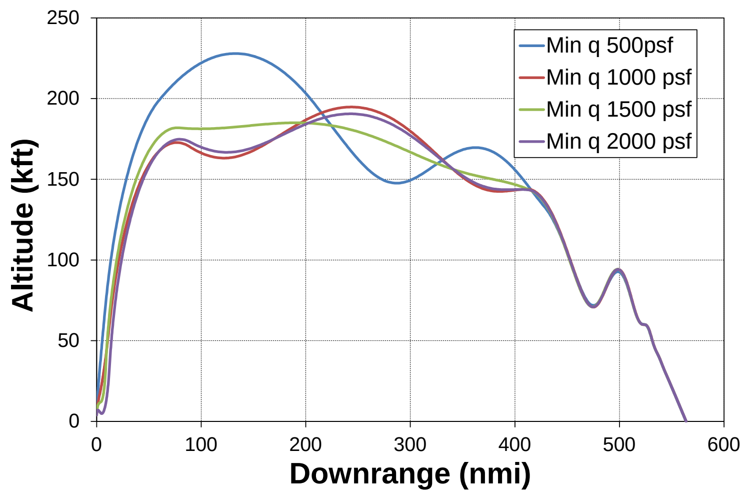

Figure 16. Altitude vs. Downrange Plot for Trajectories where Minimum Dynamic Pressure was Constrained.

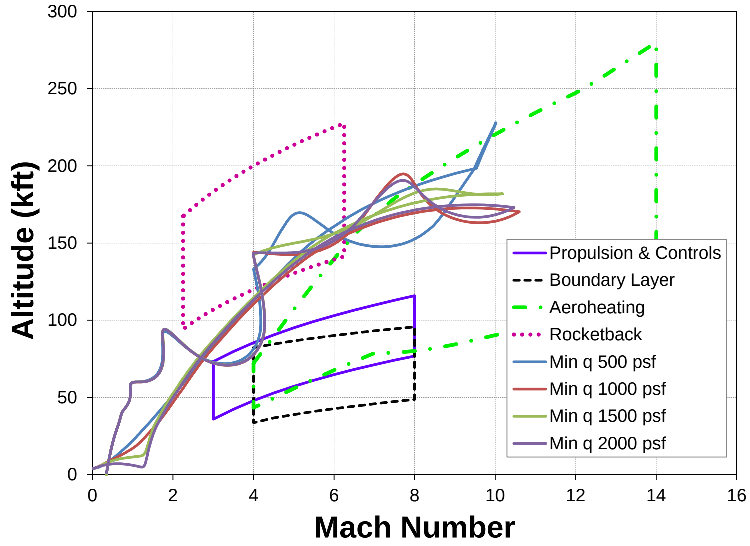

Figure 17. Altitude vs. Mach for Trajectories where Minimum Dynamic Pressure was Constrained. Trajectories are Plotted Against Hypersonic Test Windows.

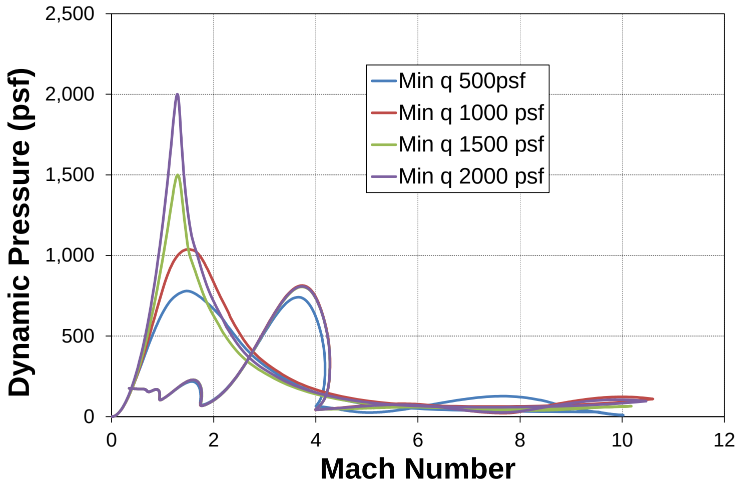

Figure 18. Dynamic Pressure vs. Mach for Trajectories where Minimum Dynamic Pressure was Constrained.

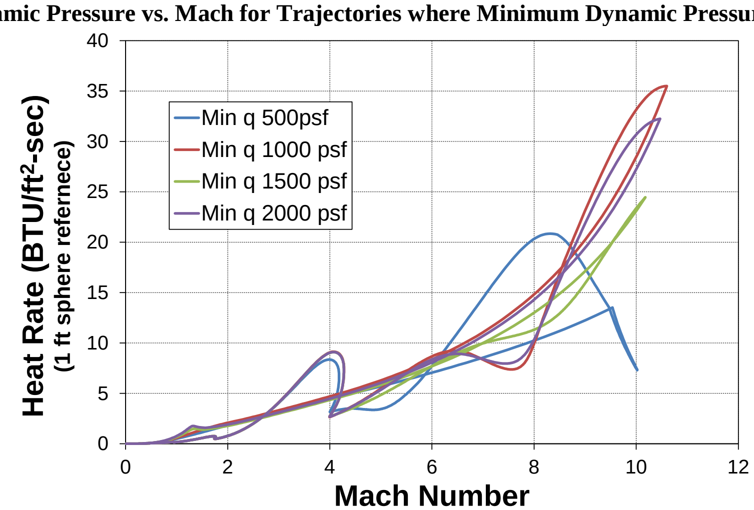

Figure 19. Heat Rate vs. Mach for Trajectories where Minimum Dynamic Pressure was Constrained.

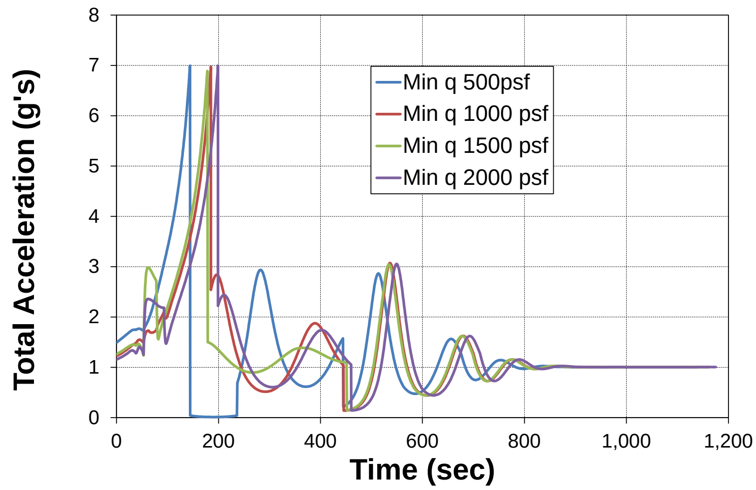

Figure 20. Acceleration vs. Time for Trajectories where Minimum Dynamic Pressure was Constrained.

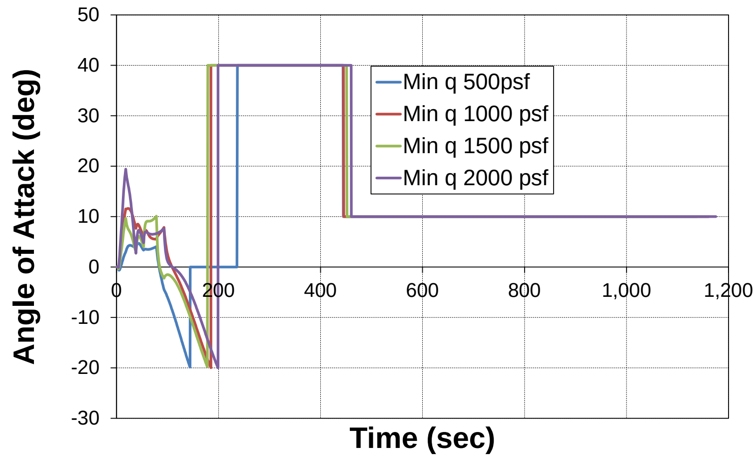

Figure 21. Angle of Attack vs. Time for Trajectories where Minimum Dynamic Pressure was Constrained.

C. Maximize Mach Number at Maximum Dynamic Pressure

This next group of trajectories changed the optimization approach from minimizing normal acceleration. The new optimization function is to maximize the Mach number at which the peak dynamic pressure occurs. The Mach 10 constraint was still applied. These trajectories were again a minimum dynamic pressures of 500psf, 1000psf, 1500psf, and 2000psf. Figure 22 through Figure 27 shows the results of these trajectories. Again these trajectories were flights from WSMR to DPG. Maximum normal acceleration was constraint to 10 g's.

As compared to the trajectories in the pervious section, the maximum altitude occurred closer to the middle rather than after the initial ascent. Again the minimum 500 psf trajectory wound up reaching a higher value. Another result as seen in Figure 24 is that the lower value of minimum dynamic pressure trajectories, the higher the Mach number at which that point occurred. Since the lower constrained trajectories were able reach a peak dynamic pressure value at higher Mach number, they were also able to reach a higher heating rate (due to heating rate being proportion to about the cube of velocity rather than the square).

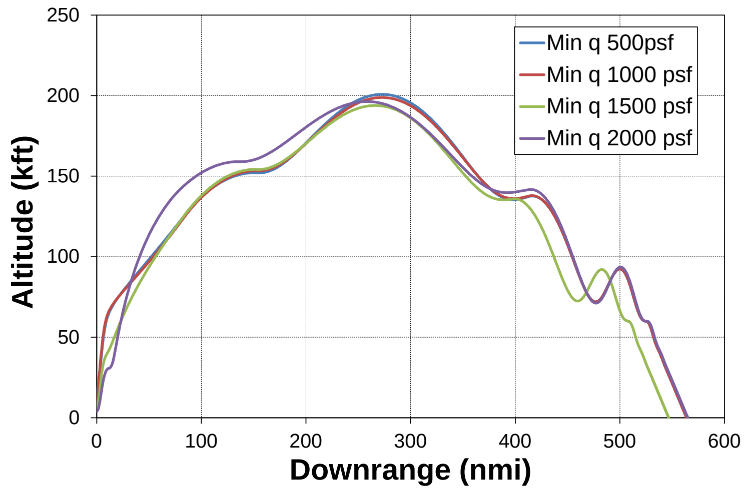

Figure 22. Altitude vs. Downrange for Trajectories where Mach number was Maximized at the Peak Dynamic Pressure.

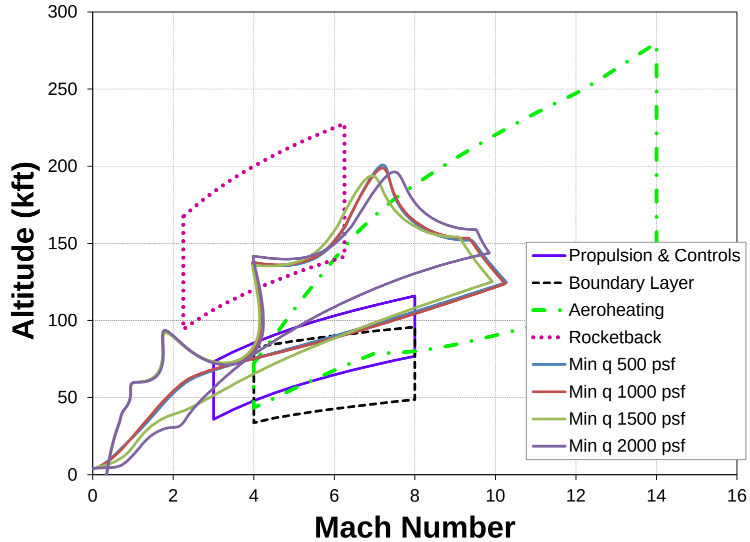

Figure 23. Altitude vs. Mach Number for Trajectories where Mach number was Maximized at the Peak Dynamic Pressure.

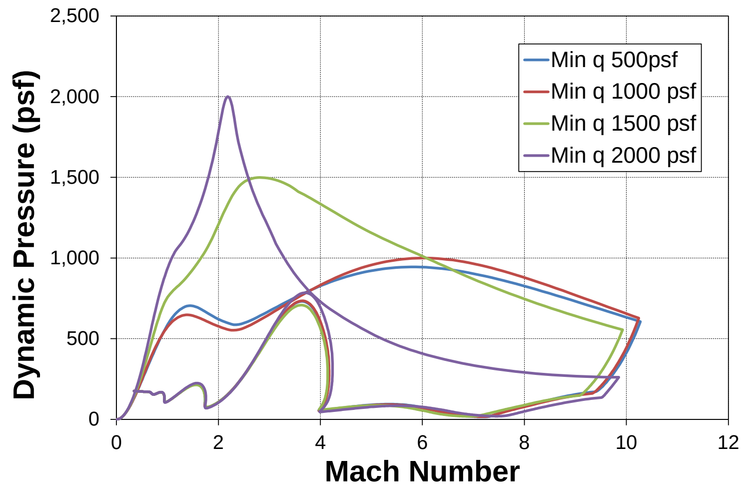

Figure 24. Dynamic Pressure vs. Mach Number for Trajectories where Mach number was Maximized at the Peak Dynamic Pressure.

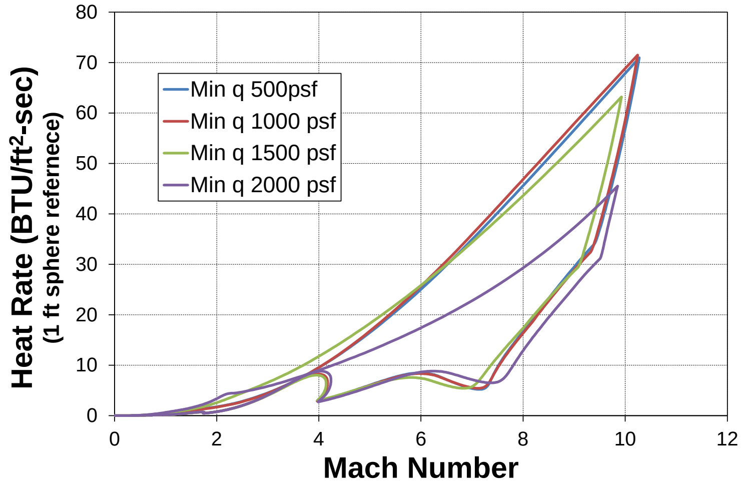

Figure 25. Heat Rate vs. Mach Number for Trajectories where Mach number was Maximized at the Peak Dynamic Pressure.

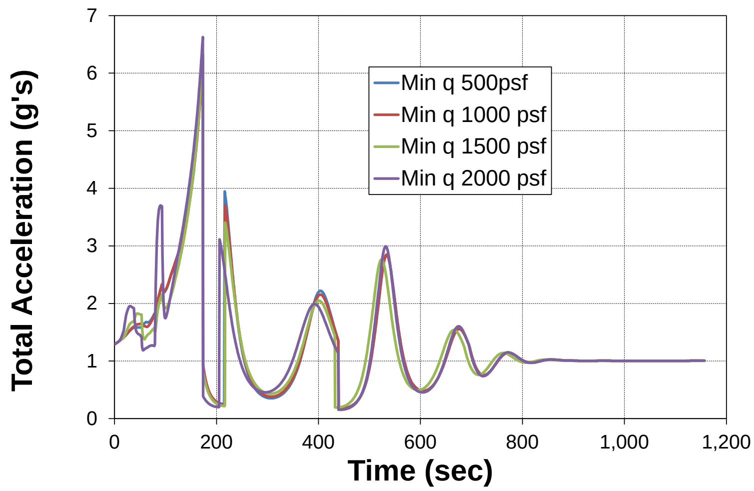

Figure 26. Acceleration vs Time for Trajectories where Mach number was Maximized at the Peak Dynamic Pressure.

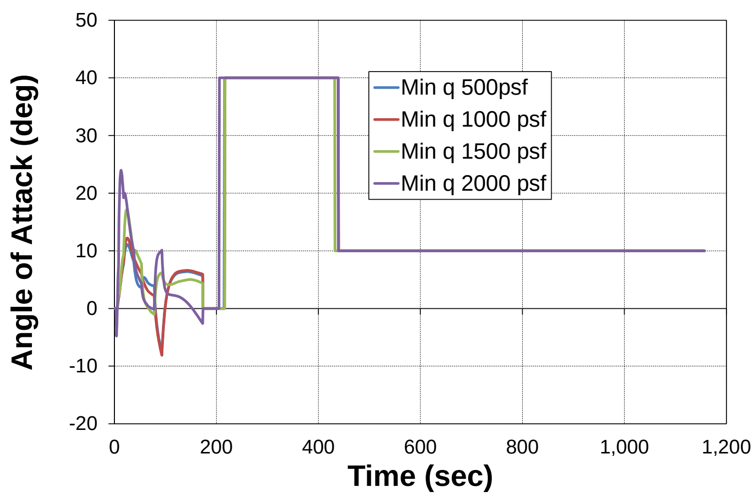

Figure 27. Angle of Attack vs. Time for Trajectories where Mach number was Maximized at the Peak Dynamic Pressure.

D. Maximize Time above Mach Number and Dynamic Pressure

For this last set of trajectories, the optimization was changed to maximize the time above Mach 5 and above a given dynamic pressure. The Mach 10 constraint was used and maximum normal accelerated was set to 10 g's. The time that each trajectory was able to remain above Mach 5 and at the specified dynamic pressure values is listed in Table II. Figure 28 through Figure 33 shows the results of these trajectories. A solution for 2000 psf was not able to be obtained given the current problem.

The most interested result is that 1000 psf and 1500 psf trajectories are nearly identical, even so that a different plotting method inconsistent with the other sections was needed to compare them. For the 500 psf trajectory, it doesn't reach Mach 5 until at a higher value (closer to 1000 psf), thus why the two trajectories are very similar. While the flight conditions vary, the 500 psf and 1000 psf trajectories were able to achieve a great deal of time at these hypersonic flight conditions. They were also able to achieve a heat rate greater than the Space Shuttle saw on re-entry (~60 BTU/ft^2*sec, see Figure 13).

Table II. Time above Mach 5 and Given Dynamic Pressure for Maximum Time Trajectories.

Given Dynamic Pressure	Time above Mach 5 and Given Dynamic Pressure Value
500 psf	1034 sec
1000 psf	1027 sec
1500 psf	14.1 sec

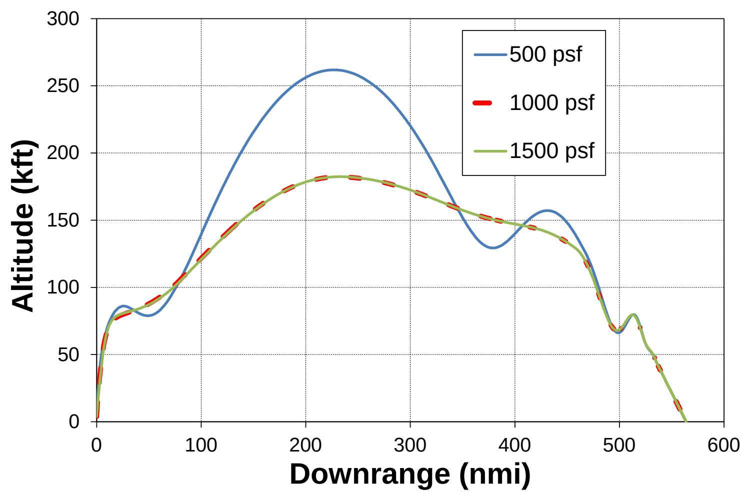

Figure 28. Altitude vs. Mach Number for Maximum Time Trajectories.

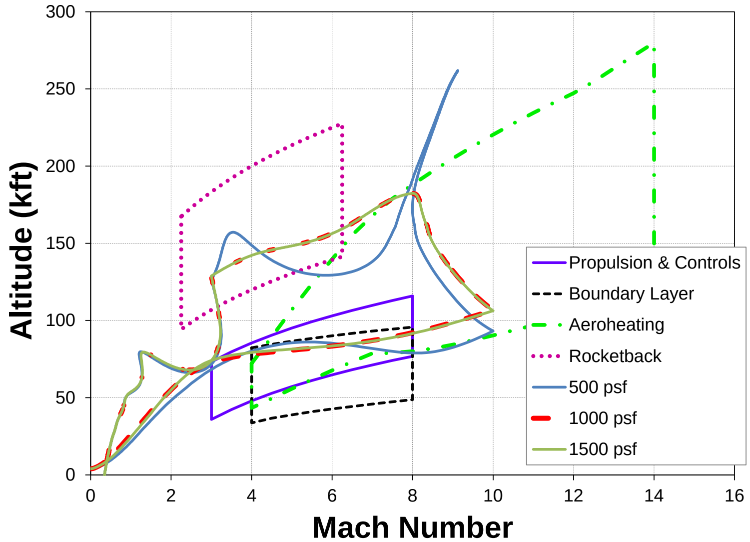

Figure 29. Altitude vs. Mach Number for Maximum Time Trajectories.

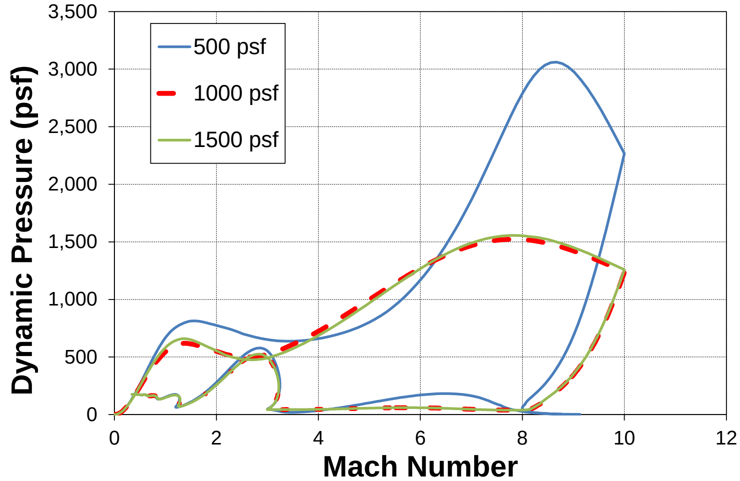

Figure 30. Dynamic Pressure vs. Mach Number for Maximum Time Trajectories.

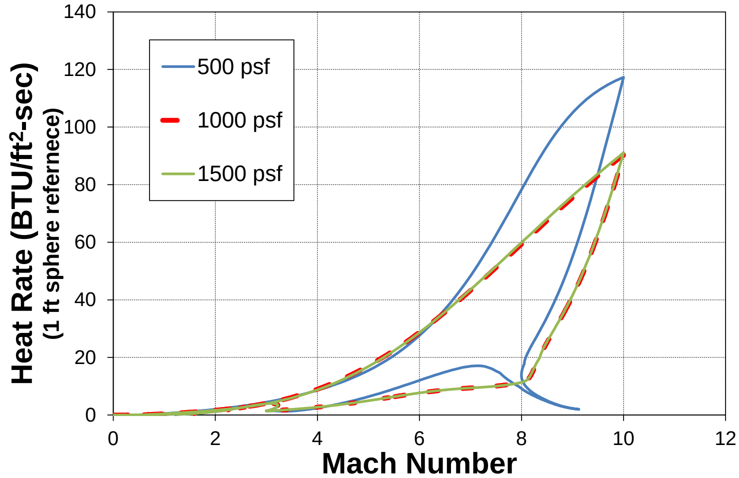

Figure 31. Heat Rate vs. Mach Number for Maximum Time Trajectories.

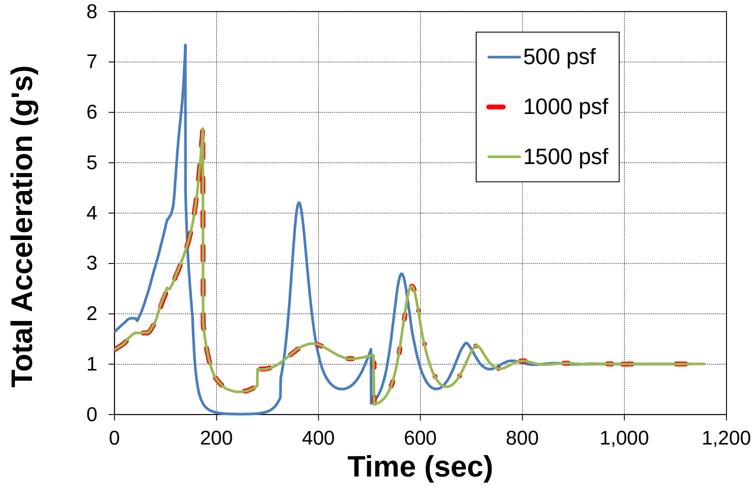

Figure 32. Total Acceleration vs. Time for Maximum Time Trajectories.

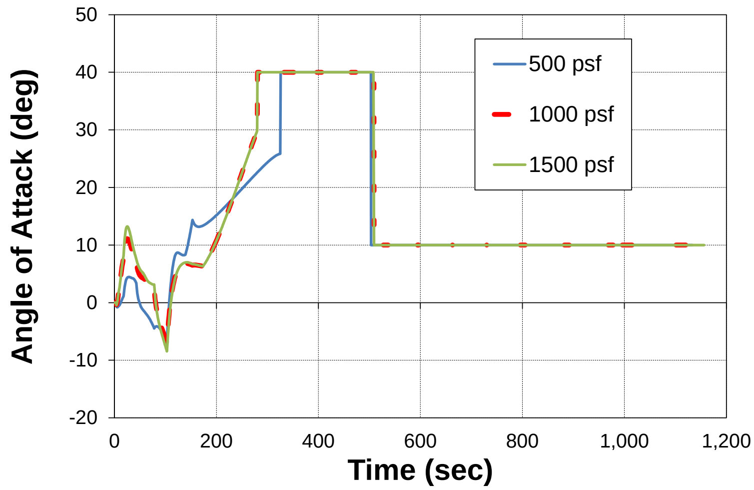

Figure 33. Angle of Attack vs. Time for Maximum Time Trajectories.

V. Conclusions

This paper presented some example approaches for designing hypersonic trajectories that meets the program objectives of the DARPA XS-1 program. Comparing the approaches for optimizing trajectories, the trajectory simulation would usually take an "easier" approach when the problem was less constrained. For example, setting a minimum dynamic pressure of 1000 psf resulted in that happening at below Mach 2 until the problem was reformulated to drive that condition to happen at higher speed (compare Figure 18, Figure 24, and Figure 30).

A major conclusion from this work is that there is a great deal of flexibility when designing hypersonic trajectories while still meeting the XS-1 Mach 10 program objective. While this paper focused on trading dynamic pressure, other values such as heat rate could easily have been used for optimization and/or constraints.

The reader should be made aware that the results presented here should be used as a starting point for trajectory design. It is very likely the local minimum were found or that other ways of posing the trajectory problem could come up with more useful results that make more sense for a flight test program.

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